LARGE-AREA MAPPING OF BIODIVERSITY[1]

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ABSTRACT

The age of discovery, description, and classification of biodiversity is entering a new phase. In responding to the conservation imperative, we can now supplement the essential work of systematics with spatially explicit information on species and assemblages of species. This is possible because of recent conceptual, technical, and organizational progress in generating synoptic views of the earth's surface and a great deal of its biological content, at multiple scales of thematic as well as geographic resolution. The development of extensive spatial data on species distributions and vegetation types provides us with a framework for: (a) assessing what we know and where we know it at meso-scales, and (b) stratifying the biological universe so that higher-resolution surveys can be more efficiently implemented, covering, for example, geographic adequacy of specimen collections, population abundance, reproductive success, and genetic dynamics. The land areas involved are very large, and the questions, such as resolution, scale, classification, and accuracy, are complex. In this paper, we provide examples from the United States Gap Analysis Program on the advantages and limitations of mapping the occurrence of terrestrial vertebrate species and dominant land-cover types over large areas as joint ventures and in multi-organizational partnerships, and how these cooperative efforts can be designed to implement results from data development and analyses as on-the-ground actions. Clearly, new frameworks for thinking about biogeographic information as well as organizational cooperation are needed if we are to have any hope of documenting the full range of species occurrences and ecological processes in ways meaningful to their management. The Gap Analysis experience provides one model for achieving these new frameworks.

Systematics is the science of describing the fundamental units that make up the diversity of life, classifying organisms in a way that indicates their natural relationships. The age of discovery, description, and classification of biological diversity is far from over. New species of chordates, the most thoroughly described phylum, are still being discovered. However, we are entering a new phase of characterizing biological diversity. This new phase is distinguished on the one hand by: (a) progress in applying concepts relating spatial scale to the hierarchy of biotic organization and more cooperative relationships among institutions that conduct research, planning, and management of biological resources; and (b) new and powerful technologies for inventorying and monitoring biological diversity. On the other hand there are setbacks due to financial limitations and a lack of societal support for the management practices that it will actually take to maintain the natural diversity of life on earth.

Clearly, the level of effort being invested in completing the description of most species and subspecies is orders of magnitude less than the level of human enterprise that results in the collateral damage of extinction and extirpation (Hawken, 1993). In order to make progress in managing for biological diversity we need to know: what species there are (systematics), how they function (behavioral and ecosystem science), how they are distributed in space (biogeography), time (population ecology), and how they are presently managed (wildlife and conservation biology). One distinct problem is that the properties of biological diversity change as the objects (individuals, populations, species, assemblages of species) are aggregated or disaggregated (Allen & Starr, 1982).

A complete biological inventory of a large area may involve, for example, describing the genetic structure of a species, its behavior, population sizes, and other metrics such as reproductive success, mortality, and mutation rates. It must describe the species' ecological positions in multiple dimensions (e.g., trophic, community affiliations, habitat, etc.) as well as the processes that maintain the ecosystems in which a species occurs. The undertaking must include studies of the biogeography of the species and the biogeography of its habitats. Finally, it must include an assessment of the current conservation status of the species and its habitats. The challenge is no less daunting than launching a 19th-century expedition to describe the flora and fauna of the Amazon Basin.

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[1] We thank the many partners of GAP for their efforts to provide biologically defensible databases that can be used in more effective interagency efforts at managing biodiversity.

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ANN. MISSOURI BOT. GARD. 85: 34–47. 1998.

So far, we have been able to document habitat-specific distributions and have obtained some sense of reproductive success over space and time for only a very few species—those that are important recreationally or commercially, or those that are rare and popular such as the California condor (*Gymnogyps californianus*) or whooping crane (*Grus canadensis*). Even for a group as intensively studied as the birds of North America, there are hundreds of species reported in fewer than ten studies in the primary ornithological literature (J. Ratti & J. M. Scott, unpublished ms.). We have just begun to study the earth as a biosphere, and the tools we are using, such as remote sensing and geographic information systems, are still developing. The challenge is to think hierarchically (Wiens, 1989) and to link the tools of geographers with those of classical taxonomists and naturalists by building two-way bridges among the disciplines. Only by increased interdisciplinary cooperation are we to have some hope of describing and understanding the complexity of nature's diversity and how to better manage our natural heritage for future generations.

We describe a method and its implementation that complements the work of systematics by focusing on two other specific parts of the biodiversity issue: biogeography and land management. The method we describe is now being carried out in the United States as the Gap Analysis Program under the Biological Resources Division of the U.S. Geological Survey (Scott et al., 1993, 1996). We present some background, methods, and results to date. Then we discuss opportunities for improving biodiversity information through better integration of systematics, ecosystem science, and biogeography.

BACKGROUND

BIODIVERSITY AND SPATIAL SCALE

Biodiversity is ". . . the variability among living organisms from all sources, including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems" (1993 Convention on Biological Diversity, Article 2, as cited in Heywood, 1995: 8). By this view, biodiversity is complex and deals with composition, structure, and process of its component parts (Noss & Cooperrider, 1994). Its characterization necessitates a synthetic hierarchical construct. Additionally, when dealing with the spatial or geographic aspects of biological diversity, clear labels and definitions for units that relate biological diversity to geographic extent are necessary.

The four basic principles that underpin the concept of hierarchy for ecology are: (1) that systems are defined by measures of their structural components and by the rates of their processes; (2) systems are ordered according to both their occurrences in space and the frequencies or rates of their processes over time; (3) larger/slower systems constrain the occurrences and behaviors of smaller/faster systems, providing the context within which the smaller/faster systems operate; and (4) the mechanisms or properties by which a system operates may not be determined only by a simple aggregation of its smaller/faster components, nor by a reduction of its larger/slower components (O'Neill et al., 1986).

When mapping elements of biodiversity over large areas, the relationships among and between the pattern of dominant land-cover types, species diversity, and spatial scale are critical. Measures of species diversity must be expressed relative to biogeographic units of a determined spatial scale if they are to be meaningful (Levin, 1981). However, confusion about the differences between types of diversity ("thematic resolution") and cartographic scale is persistent (e.g., Short & Hestbeck, 1995; Davis, 1995; Edwards, 1995; Scott et al., 1995). We suggest using seven categories as a framework for describing species diversity in relation to ecological patterns and spatial scale (Table 1; Whittaker, 1960, 1977).

The linkage between types of diversity and spatial scale makes this framework especially useful. Figure 1 (Stoms & Estes, 1993) shows how four of these categories ("inventory diversities") are used to describe species diversity *within* sampling units of four approximate sequential sizes and corresponding with four hierarchical levels of biotic organization: a single ground sampling point (*point diversity*), a natural community (*alpha diversity*), a landscape (*gamma diversity*), and a large geographic region (*epsilon diversity*). Three other terms ("differentiation diversities") are used when comparing the amount of change in species composition *between* individual sampling points (*pattern diversity*), natural communities (*beta diversity*), and landscapes (*delta diversity*) (Whittaker, 1977).

The critical point here is that the magnitude of alterations to land and water characteristics, formerly limited in spatial extent and pattern so as to be manifest at the levels of populations and species, is now so extensive that changes are manifest at the levels of natural communities, landscape ecosystems, and global ecosystems (Heywood, 1995;

Table 1. Spatial categories of species diversity (Whittaker, 1977; Stoms & Estes, 1993).

Inventory diversities	Differentiation diversities
1. *Point diversity:* A small, or microhabitat, sample of species diversity from within an alpha unit. Generally 10 to 100 square meters.	
	2. *Pattern diversity:* The change in diversity between points within a community.
3. *Alpha diversity:* A single within-habitat measure of species diversity regardless of internal pattern. Generally 0.1 to 1000 hectares.	
	4. *Beta diversity:* The change in diversity among different communities of a landscape; an index of between-habitat diversity.
5. *Gamma diversity:* The species diversity of a landscape made up of more than one kind of natural community. Generally, 1000 to 1,000,000 hectares.	
	6. *Delta diversity:* The change in diversity between landscapes along major climatic or physiographic gradients.
7. *Epsilon diversity:* The species diversity of a broad region of differing landscapes. Generally 1,000,000 to 100,000,000 hectares.	

Vitousek et al., 1996; Vitousek et al., 1997). Conservation efforts implemented at the population and species level alone may no longer be effective when system-wide changes are being forced at the landscape and global levels of ecosystem functioning. Furthermore, the properties by which a system interacts with the agents of change may not be readily identified by an aggregation of a system's smaller components or by a reduction of its larger components. Information derived from synoptic observations of both the level of biotic organization and the geographic extent at which the changes are being induced is needed (Jennings & Scott, 1993).

We believe that providing a rangewide elemental basis for assessing biodiversity conservation using maps of vegetation types and vertebrate species distributions creates sampling frameworks from which unbiased samples for more detailed studies of species occurrences, density, and viability may be made. For the first time, we can be spatially explicit about a suite of species that co-occur in a repeating pattern across the landscape, for example, those characterized by the dominance of ponderosa pine (*Pinus ponderosa* Douglas ex Lawson & C. Lawson). We can understand the extent of its occurrence as context, examine its landscape position, and make inferences about composition, structure, and function that are rangewide. The result is a significant advancement over being limited to conclusions about the ponderosa pine vegetation alliance only from stand-level examinations.

In a similar fashion, we may use the distribution map, for example, of a wolverine (*Gulo gulo*) to ask questions about the representativeness of extant collection records, or view it as a testable hypothesis and conduct wolverine surveys to document not only presence/absence but also abundance and reproductive success. We may also use these maps to make more detailed descriptions of its habitat from an unbiased sample of its entire range, all in such a manner that inferences may be made about the wolverine or its habitat (or in the earlier case, ponderosa pine) rather than simply the study site we chose to sample.

PURPOSE

The purpose of gap analysis is twofold. The first is to provide regional conservation assessments of native vertebrate species and natural land-cover types. The second is to facilitate the application of this information to land-management activities. These goals are accomplished by (a) mapping the vegetation alliances (FGDC, 1996; Grossman et al., 1994) of the United States; (b) mapping predicted distributions of each native vertebrate species; (c) mapping the existing conservation lands and ranking them by their management status; (d) determining the degree of representation that vertebrate species and land-cover types have in conservation lands; (e) providing this information to the public and those entities charged with land-use research, policy, planning, and management; and (f) building institutional cooperation in the application of this information to state and regional management activities. This, then, provides an objective database of biogeographic information that allows researchers, planners, and managers to stratify the land surface for work at higher resolutions (Scott et al., 1993, 1996), and to understand the regional and continental context of higher-resolution information from smaller areas (Jennings, 1995).

DEVELOPMENT

The term "gap analysis" refers to the process by which species and natural communities not adequately represented in conservation lands are identified. These are the "gaps" in our present-day efforts to maintain biological diversity, and it is these that are most likely to become endangered with extinction in the future. By understanding what these gaps are and where they are, future conservation crises and conflicts may be avoided.

The development of the Gap Analysis Program (GAP) began in 1987 in response to the need to complement species-by-species management of endangered species in dealing with broad-spectrum habitat loss (Scott et al., 1987, 1993, 1996). There was a need for synoptic and spatially explicit information on the distribution of each native vertebrate species and natural community, and their management status. At the time, there were no readily available, consistent data that could provide for an understanding of either the context of a single land management decision or the occurrence of a species' habitat in the ecological contexts of landscapes or bioregions.

There are many other uses for these data. Most states do not have current maps of land cover, and GAP is the first state- and national-level effort to produce this information at resolutions usable by land managers, planners, scientists, and policy makers (Scott et al., 1987, 1993, 1996). Maps showing the distributions of land cover, habitat type, vertebrate species, land management, or combinations thereof can be generated regionally or nationally. Such information may be used to identify areas that are suitable for development and where other land-use conflicts may be avoided, as well as those areas important for meeting conservation needs.

In the years since 1987, significant barriers to mapping elements of biological diversity across large areas have been overcome (Scott et al., 1996). A wide range of tools for mapping natural land-cover and habitat types and predicting vertebrate species distributions has emerged, and procedures have been refined, tested, and further refined. There is still room for improvements; additional development and testing of some methods at varying spatial and thematic scales (for example, accuracy assessment) and land-cover mapping is still needed.

COOPERATION

The U.S. Geological Survey's GAP is conducted as state-level projects, and currently there are 46 active or completed projects. Although coordinated and primarily funded by the U.S. Geological Survey's Biological Resources Division (formerly the National Biological Service), GAP is made up of over 450 cooperating organizations, including universities, businesses, and state and federal agencies.

Of equal importance to the technical progress is the way natural resources institutions (private and public) are coalescing around the concept of a standard large-area information base (one way this may be seen is through the "bottom-up" organization (and funding) that characterizes the program). GAP, the largest effort ever mounted to map selected (i.e., vertebrate species and vegetation types) biological resources of the United States, is being carried out cooperatively by state-level projects.

The importance of having data sets that are comparable across state boundaries is in revealing actual patterns of species and vegetation community distribution at scales relevant to both the magnitude of present-day changes and the multiple levels of biological organization. Such information may be used to identify areas that are suitable for development and where land-use conflicts may be avoided, as well as those areas important for meeting conservation needs. New frameworks are emerging for both in the new type of information being developed and in the convergent way it is being developed.

There is now convergence on mutually recognized and systematic definitions for natural communities as intrinsic entities and as habitat types, for example, as indicated by the land-cover classification system being proposed for adoption by the Federal Geographic Data Committee (FGDC) and by formation of the Ecological Society of America's Vegetation Classification Panel. There has been substantial recent progress on methods for mapping alliances of natural communities, as represented by dominant natural vegetation or non-vegetated land-cover types, though it appears that no single method will suffice for all environments (Caicco et al., 1995; Stoms, 1994). There is increasingly more common ground on methods for predicting the dis-

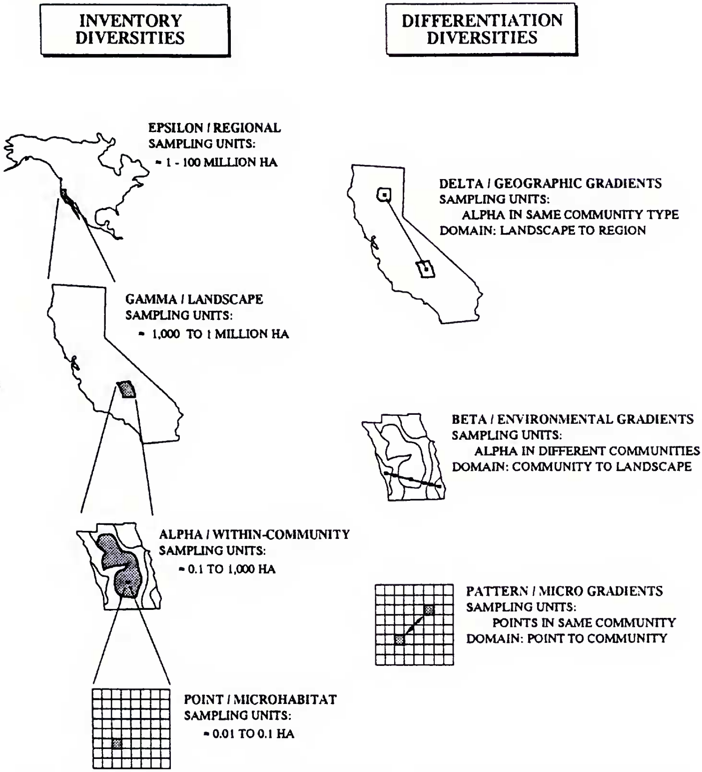


Figure 1. Diagram showing seven spatial levels of species diversity defined by Whittaker (1977). The lefthand column represents levels of diversity within a spatially sequential set of sample units, or "Inventory Diversities." The righthand column represents categories of species change in composition between or among sample units of the same spatial level. (From Stoms & Estes, 1993, reprinted with permission.)

tribution of native vertebrate species (Butterfield et al., 1994; Edwards et al., 1995). And, much experience has been gained in the mapping of areas that are managed for biodiversity (Beardsley & Stoms, 1993). Although many issues remain, such as accuracy assessment and appropriate scale and resolution, much attention is being brought to bear on them, and the trends are quite positive.

Frameworks are now in place in GAP, as well as in other large-scale biological assessments, for generating, archiving, distributing, querying, and experimenting with biological data that cover large areas, and there is a great deal of interest in improving the science of these efforts. What might be of greater significance is that consensus on these issues is taking place among state-level institutions as well as among the state and national interests who have responsibility for research and management of natural resources.

The concept underlying this dynamic is that it is far more important now, while land use decisions concerning millions of hectares are being made daily, to begin with an accounting of the conservation status for the mappable elements of biological diversity than to put off any real action until perfect methods have been conceptualized, and all elements of biodiversity have been identified and mapped, tested, published, replicated, adopted, diffused, and applied. There is simply not the time, money, nor political will to take that path. Today we have the capabilities to build powerful sets of information, imperfect though they may be, that correspond to the multiple levels of biotic organization. And we have the ability to foster the application of that information, by all concerned, to solve the seemingly inexorable problems of maintaining our biological heritage. It requires that professionals and their institutions put aside their past disciplinary and institutional differences, assume some risk, and commit to work together with whatever resources they have. This can result in a leveraging of funds and minimizing of duplicate efforts.

METHODS

GAP requires computer-based (digital) maps of: (a) existing natural or semi-natural land cover to the level of community alliances (vegetation types characterized according to their dominant or co-dominant plant species or, in the absence of a dominant vegetation species, dominant land-cover feature (Grossman et al., 1994)); (b) predicted present-day distributions of native vertebrate species; and (c) public land ownership and private conservation lands. These data layers are analyzed to compare distributions of each native vertebrate species, group of species, and community alliance with the existing network of conservation lands. Results show where the conservation "gaps" are in both land management and in the body of knowledge about species and natural communities. An overview of the methods for developing each of these three data sets is presented below (see also Scott et al., 1993; Jennings et al., 1996; Gap Analysis Program World Wide Web home page http://www.gap.uidaho.edu/gap).

LAND COVER

Generally, the mapping of land cover is done by delineating areas of relative homogeneity (basic cartographic "objects"), then labeling these areas using categories defined by a land-cover classification system. More detailed attributes of the individual areas are added as more information becomes available, and a process of validating both polygon patterns and labels is applied for editing and revising the map. This is done in an iterative fashion, with the results from one step causing reevaluation of results from another step. For example, the discovery of attributes for a given mapped polygon may result in adjustment of its boundary. Finally, an assessment of the overall accuracy of the data is conducted. Where the database is appropriately maintained, the final assessment of accuracy will show where improvements should be made in the next update (Davis et al., 1995).

Some of the problems with efficient mapping of large areas at the desired spatial and thematic resolutions (i.e., 1:100,000-scale and community alliance theme) that have been overcome are: (a) classification of land cover, (b) data acquisition, (c) delineation of land-cover pattern, (d) object interpretation (Orians, 1993), and (e) assessment of final map accuracy. In order to provide meaningful comparisons across large areas, a consistent land-cover classification system is needed. Land-cover classifications must rely on specified attributes such as the structural features of plants, their floristic composition, or environmental conditions to differentiate categories evenly (Küchler & Zonneveld, 1988). Although there has been much effort devoted to the classification of vegetation, there has been no previous attempt to apply a detailed classification of natural land cover across the contiguous 48 United States at a 1:100,000 scale, although Crumpacker et al. (1988), assessed the occurrence of 135 potential vegetation types on federal and Indian lands. In mapping land cover, GAP uses the National Vegetation Classification (FGDC, 1996, 1997; Grossman et al., 1994; Bourgeron & Engelking et al., 1994; Sneddon et al., 1994; Weakley et al., 1996; Loucks, 1995, 1996).

The minimum thematic object that Gap Analysis is mapping is the community alliance (Grossman et al., 1994; see Appendix 1 for a sample description of a community alliance), although in practice for some areas, mosaics of undifferentiated alliances (e.g., "oak woodlands" rather than "*Quercus garryana* alliance") represent the limit of current capabilities to map land cover across ecoregions and biomes. The alliance corresponds most closely with the units of alpha diversity (a sample representing a community regarded as homogeneous despite its internal pattern) in order to conduct analyses at the beta, gamma, delta, and epsilon levels. A spatial depiction of beta diversity (between-habitat diversity) represents the pattern of landscape, or gamma, heterogeneity. For Gap Analysis, the central concept is that the structural and floristic characteristics of dominant vegetation or (in the absence of vegetation) dominant land features, can be used systematically to delineate and map patterns of beta and gamma diversity. Models of these patterns are important for generating and evaluating landscape-level conservation options.

For the delineation of land-cover patterns, the Landsat Thematic Mapper (TM) satellite images serve both as a base map and as a source of spectral information for discriminating among land-cover types. Although methods for preprocessing the basic TM product used in mapping land cover were variable at the earlier stages, currently state projects use a standard TM product that is geographically registered to within 30 m, corrected for terrain distortion and systems errors, and spectrally classified into 240 classes using bands 1, 2, 3, 4, 5, and 7 (see Bara, 1994).

No single procedure is appropriate for the delineation of land-cover patterns in all environments of the United States (Davis et al., 1995), and a variety of methods are used to delineate land-cover patterns by the GAP state project analysts (Davis et al., 1991; Davis & Stoms, 1996; Davis et al., 1995; Edwards et al., 1995; Lillisand, 1996; Scott et al., 1993; Slaymaker et al., 1996). As pattern is delineated, the resulting objects are interpreted and labeled in an iterative fashion. To recognize vegetation alliances, training images of each type are identified on the ground. Air photos or air videos are being used to train analysts. Additional data sets, such as digital elevation models, temperature and precipitation patterns, and soils maps, are also used. A single, precisely standardized method for pattern delineation is not possible because: (a) vegetation characteristics differ substantially among biogeographic regions, requiring different approaches, especially for interpretation of remotely sensed data; for example, the use of TM imagery from different seasons may be used singularly in a false color composite format and interpreted visually, or their spectral values may be transformed in a specific way and merged together to reveal patterns based on phenotypic distinction (the possible variations are almost endless); (b) the expertise for vegetation typing and mapping is itself also regional in nature, resulting in different approaches by the state project scientists; (c) many different sources of information are used to render the maps (for example, variability in the date of imaging among TM scenes within a state and wide variation in the availability of information about the occurrence of dominant cover types from state to state), introducing variability into the product; (d) the current mapping work is a first generation effort, with significant improvements to the technology being made by the state GAP projects; there is a need to try different methods because an effort of this magnitude, extent, and degree of resolution has not been undertaken before; (e) of necessity, GAP is a collaborative "bottom-up" effort focused on pragmatic, near-term conservation, and at present there is neither the institutional support nor the time to research and develop a single method, achieve consensus on such a method, then implement a large "top-down" program.

Each map class of the state-level spatial data sets is tested for accuracy, using independent field data, with the confidence interval carried through further transformations with that data set's metadata. A detailed review of data quality is undertaken when edge-matching data from adjacent states. Since the present effort is a first generation one, improved methods are expected to dampen the amplitude of inter-state variation in later generations as well as increase thematic resolution and accuracy. A number of land-cover data sets from states that used different methods have been edge-matched with good results (M. Murray, Idaho Cooperative Fish and Wildlife Research Unit, C. Homer, Utah Cooperative Fish and Wildlife Research Unit, and R. Redmond, Montana Gap Analysis Project, Missoula, pers. comm.).

VERTEBRATE SPECIES DISTRIBUTIONS

The objectives for mapping the distributions of vertebrate species are to provide maps of known confidence in order to support analysis of conservation status to develop a database of locational records, geographic range, wildlife habitat associations, and predicted distribution of each vertebrate species for the long-term utility for GAP and its cooperators.

Most existing information on species distribution has typically been collected at the scale of individual field sites and extrapolated to small-scale range maps for state, regional, or national references and field guides. Lacking for most biogeographic information on species is a meso-scale expression (e.g., 1:100,000) of a detailed distribution map, as compared with a general range map depicting broad regional or continental limits.

The basic assumption of GAP's predicted species distribution maps is that a species has a high probability of occurring in appropriate habitat types that are within its predicted range. GAP links species' general ranges to large-area land-cover maps and other physical data, which are intermediate in scale between a known specimen collection site and a field guide range map (see Edwards et al., 1996;

Scott et al., 1993). This approach is derived from the assumption that, for large areas such as states or nations, it is impractical to map the distribution of species at a nominal scale of 1:100,000 only from intensive field surveys. GAP therefore makes use of existing information on range limits and refines it to develop spatial statements of the presence and absence of a species in map polygons that represent appropriate habitat as understood from current knowledge of the species and the ability to map its habitat (Scott et al., 1993; Butterfield et al., 1994; Edwards et al., 1995).

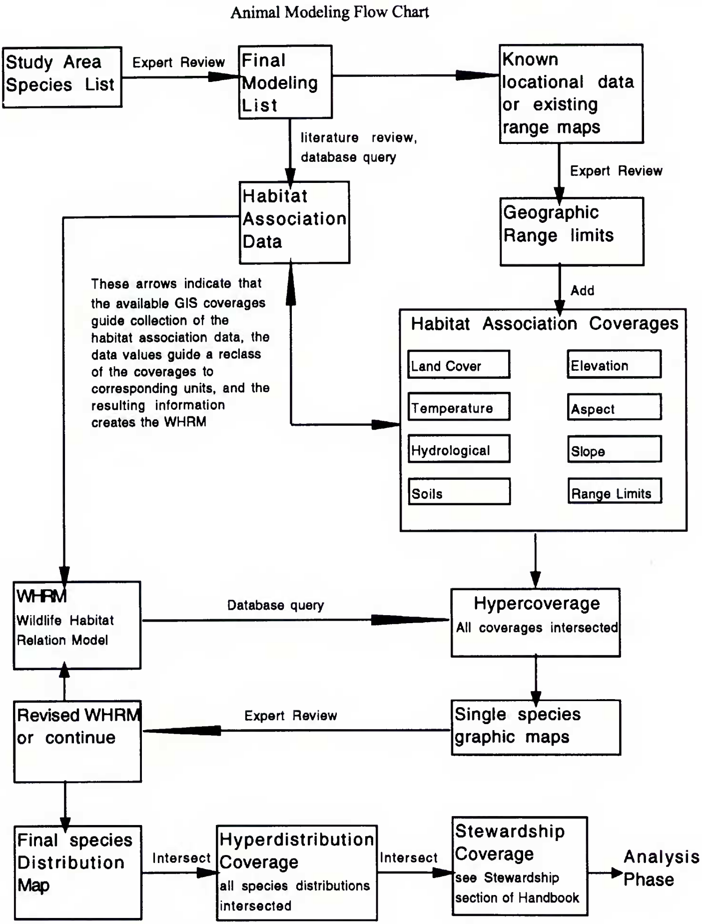
Predicting species distributions by relating them to environmental features that can be mapped from remotely sensed data is an efficient approach to estimating the distribution and management status of elements of biodiversity. However, no matter what their scale, *all* range and distribution maps are predictions about the presence of a species in a particular geographic area. The accuracy of those predictions generally improves as the size of the area, length of the sampling period, and intensity of sampling are expanded because greater temporal scale as well as heterogeneity of large areas make it more likely that a species will be found to occur there. GAP maps of predicted distributions are currently intended for use and validation at the landscape, or gamma, level of diversity (an area made up of more than one kind of natural community, generally, 1000 to 1,000,000 ha; Whittaker, 1977), but new efforts are able to attribute species to "patches" as small as 2 hectares. For some species, such resolution may be desirable to allow more precise estimation of habitat area, while for other species, such small patches may be biologically meaningless. For the majority of species, the ability to map at this resolution probably exceeds our knowledge of their ecology.

We mapped predicted vertebrate species' occurrences by first obtaining specimen collections and verified sighting records for specific known locations for each species and entering this information into a database. These records are considered as either current (within the past 10 years) or historical (> 10 years old). Second, the general range extent for each species is established from the best available information—frequently field guides. Third, an exhaustive literature search is done to establish the known habitat relationships (vegetation, elevation, lakes, etc.) for each species. Fourth, a habitat relationship model for each species is constructed for use in a geographic information system (GIS). Fifth, the range units and habitat associations are integrated into a predicted species-distribution map, with areas attributed by known versus predicted occurrences. Sixth, an expert review of the draft maps is conducted, the maps are edited, and all changes are documented (Csuti & Crist, in prep.). The resulting maps are testable hypotheses, predictions we hope will be improved with better information over time (Fig. 2). This type of database bootstrapping is critical if we are to overcome both sparse data and funding constraints. At the landscape level of resolution, GAP predictions of accuracy have ranged from 70% to over 90% for birds, mammals, amphibians, and reptiles (Edwards et al., 1996; Scott et al., 1993; C. Peterson, Idaho State University, pers. comm.). The procedure works best for species with habitat preferences that can be described in terms of land cover and other mapped features or characteristics. It works for habitat specialists only if their specific habitat requirements are available as mapped features or are well associated with other mapped characteristics such as land-cover types. An additional caution is that species with very restricted distributions cannot reliably be predicted to occur in seemingly appropriate habitat within their general distributional limits. Because of their rarity, these species are often the subject of special attention from state and federal resource agencies. The specific locations where they are known to occur are usually tracked by Natural Heritage Programs (NHPs) and Conservation Data Centers (CDCs). GAP makes use of the data from Heritage Programs and CDCs to report the presence of populations of such species within a mapped unit. For security purposes, the exact locations of these populations are distributed only by the NHPs or CDCs.

LAND-OWNERSHIP AND LAND-MANAGEMENT MAPS

Since one purpose of GAP is to provide an assessment of the conservation status of species and their habitats, maps of lands that are managed for conservation must be compared with the distributions of species and habitats. Most states, however, do not have a current inventory of land-management status. The first step toward developing a map of conservation lands is to map land-ownership by the major categories of (1) public lands by managing agency, (2) voluntarily identified privately owned conservation lands, and (3) all other privately owned lands. Then, as a second step, the attributes for land-management categories are added to these tracts. All non-conservation privately owned lands (category 3 above) are simply labeled "private," and individual parcel boundaries are not delineated.

Land-ownership and land-management maps in-



These arrows indicate that the available GIS coverages guide collection of the habitat association data, the data values guide a reclass of the coverages to corresponding units, and the resulting information creates the WHRM

Figure 2. The gap analysis wildlife habitat relationship model.

clude land parcels that can be reasonably resolved at a 1:100,000 scale. Commonly this is 1 ha, which is equivalent to 1 mm² on a 1:100,000 scale map. Descriptions of how the land-management maps are developed are provided by Scott et al. (1993), Beardsley and Stoms (1993), and Edwards et al. (1995). Land-management is ranked by the four levels shown in Table 2.

Over the past year, there has been an ongoing discussion among GAP participants about the ad-

Table 2. The four levels of land management and their definitions.

Level	Definition
1.	Areas having a management plan in operation to maintain a natural state and within which natural disturbance events are allowed to proceed without interference.
2.	Areas generally managed for natural values, but which may receive uses that degrade the quality of existing natural communities.
3.	Areas for which legal mandates generally prevent permanent land cover conversions from natural or semi-natural habitats to anthropogenic habitats, such as conversions to agriculture, but which are subject to extractive uses such as silviculture or mining.
4.	Areas managed for intensive human uses.

equacy of these definitions. Many feel a larger number of categories that use a wider variety of management activities undertaken on behalf of native species and ecosystems would be more useful. When a greater number of management categories was recognized during the Sierra Nevada ecosystem project and species were rated differently within these categories because of their varying responses to management practices, communication among cooperators was greatly improved (F. Davis, University of California, Santa Barbara, pers. comm.). As a result, GAP is exploring a land-management scheme having greater thematic resolution.

ANALYSES

While there are many ways that the three basic data sets of land cover, vertebrate distributions, and land management may be analyzed, the primary purpose is to identify potential gaps in the existing network of conservation lands. The identification of conservation gaps is intended to provide land stewards with the information needed to modify their plans and practices in order to maintain our natural biodiversity and the processes that sustain it, and to avoid conflicts with other uses of the land.

The analysis presented here focuses on the basic requirements for a state gap analysis project. These call only for identification of those biotic elements that lack adequate representation in conservation lands rather than the identification of specific geographic locations needed to "plug" the gaps. The latter is the selection phase of reserve design and requires detailed on-the-ground information concerning habitat quality and demographics of the species of interest. The first objective is to determine the representation of each mapped alliance and vertebrate species in each category of land ownership and management status. The second objective is to interpret the analysis in a way that is useful for land stewards in land-use planning and management for conserving those biotic elements. The program provides the data sets and the analyses in forms suitable for additional modeling, biodiversity assessment, and planning activities.

These objectives are met by intersecting the land-cover and animal ("element") distribution GIS coverages with the land-ownership and land-management coverage so that the element coverages incorporate the stewardship boundaries. Then, the statistics from that intersection are used to generate a table reporting the representation of individual elements (species and dominant cover types) in each ownership and management category. Finally, these results are used to generate maps of those elements found to be lacking in their representation in conservation lands, and they are incorporated into a standard final report. Each species and plant community alliance is identified and analyzed separately. Selected groups of elements of interest may also be analyzed. For example, a spatial analysis of species having less than 10%, 20%, and 50% of their distributions in status 1 or 2 (Table 2) land-management areas is provided. Other groups of species of special interest (e.g., endangered species or declining neotropical migrant bird species, and endemic species, etc.) may also be analyzed for their representation in conservation lands.

There are clearly some limitations to this approach. One is that the historical distributions of elements are usually poorly known; measures of present-day distributions usually cannot indicate the extent of loss in historical range (but see Noss et al., 1995). For example, if an element has already been reduced by 90% from its historic distribution, and gap analysis indicates a 50% occurrence in management status 1 or 2 areas, the result is that only 4.5% of its historic distribution is represented. Another limitation is that GAP currently does not predict element viability. For most species and plant communities, viability measures such as habitat quality, species abundance, population trends, reproductive success, and mortality at a site are unknown and cannot be assessed given current knowledge. Therefore, GAP only provides information on representation with the objective of highlighting at-risk species and vegetation types that should undergo viability analysis as a next step. GAP is the first phase of identifying a three-part process that also includes reserve selection and design. Generally, conservation assessment of animal species must be used with more caution than assessment of land-cover types because land-cover maps are actual, typically with a statistically valid accuracy assessment, while animal distributions are predicted and difficult to validate. Land-cover types are more stationary and change slowly, while animal species are mobile and can expand and contract ranges over relatively short time spans; effects of management status on land-cover types are generally easier to predict than effects on animal species.

RESULTS AND DISCUSSION

Prior to the development of spatial data by GAP, the information needed to assess the conservation status of all but a few of the most popular vertebrate species was not available in the United States. There were no geographically extensive maps or databases of species distributions or actual dominant vegetation types at cartographic scales usable by local land managers. For example, Klopatek et al. (1979) estimated that 34% of the land surface in the United States was subject to some form of intensive land use. The authors concluded that 23 of the 106 types of potential (or original) vegetation may have been reduced by over 50%. Much more significantly, though, they concluded that there were major drawbacks and limitations to their findings because no inventory of actual vegetation existed at that time. They relied on general predictions of the occurrence and extent of potential vegetation for baseline data and compared those hypothetical data with nonstandardized estimates of county-level land-use practices. The critical information has, until now, been unavailable at the level of resolution necessary for large-area management of ecological systems.

We believe that a comprehensive plan for protecting our nation's biodiversity must include a representation of species and vegetation communities across their full range of geographical occurrence and ecological expression. The latter is being made possible by the development of standard catalogs and classification of the nation's vegetation types (Bourgeron & Engelking, 1994; Sneddon et al., 1994; Weakley et al., 1997; Drake & Faber-Langendoen, 1997; FGDC, 1997; ESA Vegetation Classification Panel, in prep.), which is overcoming the lack of a standardized system of vegetation classification (Orians, 1993). There is some confusion as to what represents a reasonable target for species or community conservation. The Endangered Species Act (ESA) currently stipulates species, subspecies, or distinctive population units. Much of the current debate over reauthorization of the ESA concerns the unit of protection, with many asking that we be more restrictive and protect only species or populations for which it can be demonstrated there is no gene flow with other populations. It is the belief of many that we have spent an inordinate amount of effort protecting subspecies and populations, although this is not borne out by the facts (Tear et al., 1993). One suggested conservation target is the natural community or the association in the National Vegetation Classification (FGDC, 1997; Jennings, 1993). However, we are currently unable to synoptically map that level of detail across physiographic provinces, ecoregions, or biomes. Examination of coarser levels such as mosaics of dominant vegetation types suggests that 16 of 30 plant communities evaluated in Utah were at risk (Edwards et al., 1995), and 32 of 71 in Idaho were considered vulnerable (Caicco et al., 1995). Thus, even at this coarser level of the GAP mapping effort, we found perhaps 25–40% of mapped vegetation types were at risk, and with them, other associated elements of biodiversity. This suggests that major progress toward protecting biodiversity could be made by simply insuring that viable examples of each of the vegetation alliances in North America be managed for their long-term viability.

However, we must be cautious. In interior maritime coniferous forest in the Pacific Northwest (Scott et al., unpublished ms.) we found the Western Red Cedar had 36% of its acreage in special management status. However, when examining the evenness of the Western Red Cedar forest alliance across its full range of ecological and geographical expression, we found its occurrence in special management areas was biased elevationally and geographically. When we examined the representation of the 16 identified and mapped natural community associations of the Western Red Cedar alliance in Idaho, we found eight with no acreage in special management areas and several with more than 80%. Thus, the more detail we have, the more informed the decision-making process of how to proceed with management. This just serves to emphasize the need for a hierarchical approach, spatially and thematically, for evaluating the effectiveness of current conservation efforts.

To date, results from Gap Analysis projects have been reported from Utah, Wyoming, Arkansas, California, Idaho, Oregon, Massachusetts, and Maine. Information from these areas has been used for land-use planning at several locations in southern California (Crowe, 1996), including Camp Pendleton and the Mojave Desert (T. Edwards, pers. comm.). It has been used to assess the contribution of proposed wilderness areas and new national parks to the further protection of biodiversity (Wright et al., 1994). Other uses include identification of new research sites and species and vegetation types at risk. But perhaps more importantly, it has served as the catalyst for new partnerships, often among individuals and organizations who had little or no history of working together. Partnerships (e.g., Crowe, 1996) forged in the data acquisition and analysis phase of the individual Gap Analysis projects have continued on into the implementation phase of GAP and into other endeavors as well.

These partnerships are deepening as we periodically update the thematic layers of GAP, and their application for more informed land-use decisions becomes an ordinary feature of natural resources management. Additional information on Gap Analysis can be found at http://gap.uidaho.edu/gap.

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Appendix 1. A Sample Description of a Community Alliance Vegetation Type (from Sneddon, 1994)

I. Class: Forest
  I.C. Subclass: Mixed evergreen and deciduous forest
    I.C.3. Group: Mixed needle-leaved evergreen and cold deciduous forest
      I.C.3.N. Subgroup: Natural/Seminatural vegetation (not cultivated)
        I.C.3.N.a. Formation: Mixed needle-leaved evergreen and cold deciduous upland forest
          I.C.3.N.a.b. Community Alliance: *Tsuga canadensis–Acer saccharum–Betula alleghaniensis* Forest Alliance

Description: Eastern hemlock, sugar maple, yellow birch, forest alliance: Forests of this alliance include mesic communities known as "hemlock ravine" and "hemlock-northern hardwoods." Communities of this alliance generally occur in mesic ravines, north-facing slopes, and other cool, moist habitats. They contain substantial amounts of *Tsuga canadensis*, as well as other components of the northern hardwood forest, most commonly *Betula allegheniensis*, as well as *Acer saccharum* and *Fagus grandifolia*. *Tsuga* may be dominant, particularly in ravines, and *Prunis serotina* is a major component in the Allegheny Mountains. Other canopy associates include *Betula lenta*, occasional *Pinus strobus*, and *Picea rubens* in northern New England. *Viburnum alnifolium*, *Diervilla lonicera*, *Sambucus pubens*, and *Taxus canadensis* occur in these communities; *Rhododendron maximum* is particularly characteristic in southern representatives of this alliance. Herbaceous flora may be sparse, but generally includes *Mitchella repens*, *Oxalis montana*, *Lycopodium lucidulum*, *Streptopus roseus*, *Medeola virginiana*, *Epigaea repens*, and *Maianthemum canadense*.

SAF type 24, Hemlock,—Yellow Birch is more or less synonymous with this alliance.

Regional Distribution: This alliance occurs in all Eastern Region states except Delaware. It also occurs in the Midwest Region and locally at higher elevations in the Southeast Region. The full range of this alliance is quite broad and is likely to be more or less coincident of that given for SAF type 24, Hemlock–Yellow Birch: central and southern Ontario, southern Quebec, south to Wisconsin and Michigan, and Cape Breton, south on the Allegheny and Catskill Mountains, central New England and the Appalachians, south discontinuously on the southern Appalachians (Eyre, 1980).